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WHO RESPONDS AND HOW LONG DOES IT TAKE: ASSIGNING FIRE STATION AREAS OF RESPONSIBILITY

by

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June 2000

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13. ABSTRACT *(maximum 200 words)* The city of Monterey, California, provides fire protection and emergency medical response (FP&EMR) for the city of Monterey, an Army facility and two adjoining communities. The city currently maintains three full-time fire stations. Within the city's boundaries lies the US Naval Postgraduate School (NPS), which currently provides its own FP&EMR, but the city is evaluating the possibility of providing this service for NPS. This thesis develops models to predict response times from NPS and city stations to emergency locations and combines these models with an optimization model to evaluate how optimal response times would vary with and without the NPS station. Results indicate that the city would marginally satisfy federal response-time requirements for NPS by operating only its current three stations: Average response is acceptable, but the variance is not. However, if the city operates the NPS station and only two of its current stations, estimated response times improve over the status quo, and variance is acceptable. Based on data for one year, city operation of all four stations would provide a 7.5% reduction in total estimated response time compared to the status quo, while using two stations plus the NPS station would provide a 4.9% reduction.

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WHO RESPONDS AND HOW LONG DOES IT TAKE: ASSIGNING FIRE STATION AREAS OF RESPONSIBILITY

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ABSTRACT

The city of Monterey, California, provides fire protection and emergency medical response (FP&EMR) for the city of Monterey, an Army facility and two adjoining communities. The city currently maintains three full-time fire stations. Within the city's boundaries lies the US Naval Postgraduate School (NPS), which currently provides its own FP&EMR, but the city is evaluating the possibility of providing this service for NPS. This thesis develops models to predict response times from NPS and city stations to emergency locations and combines these models with an optimization model to evaluate how optimal response times would vary with and without the NPS station. Results indicate that the city would marginally satisfy federal response-time requirements for NPS by operating only its current three stations: Average response is acceptable, but the variance is not. However, if the city operates the NPS station and only two of its current stations, estimated response times improve over the status quo, and variance is acceptable. Based on data for one year, city operation of all four stations would provide a 7.5% reduction in total estimated response time compared to the status quo, while using two stations plus the NPS station would provide a 4.9% reduction.

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The reader is cautioned that computer programs developed in this research may not have been exercised for all cases of interest. While every effort has been made, within the time available, to ensure that the programs are free of computational and logic errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the user.

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EXECUTIVE SUMMARY

Current operating regulations prohibit the fire station at the US Naval Postgraduate School (NPS), Monterey, California, from responding to emergency calls outside of NPS property, even if a call is within 300 feet of the station. Instead of an estimated response time of 1.7 minutes from the NPS station, such a call must wait 5.1 minutes for a fire station in the city of Monterey to respond; the difference is valuable time that could help prevent property damage and loss of life. How much better would the situation be without these current regulations? This thesis provides quantitative analysis to answer this and related questions.

This thesis, requested by the city of Monterey and NPS, evaluates an opportunity created under Public Law 103-337, Section 816 (US Code 1994) that allows the city of Monterey to supply fire protection and emergency medical response (FP&EMR) to NPS, a 0.9 square mile naval facility located within Monterey.

The primary measure of effectiveness this thesis uses is *response time*, the time between a call that leads to the dispatch of an emergency vehicle and that vehicle's arrival at the scene of the emergency. Historical response times cannot be used for station-to-subdivision dispatches that did not occur—a *subdivision* is a small, homogeneous section of the city—so linear time-distance regression models are developed to provide those *estimated response times*, which predict the average time between a call dispatching an emergency vehicle and the vehicle's arrival at the scene of the emergency.

A *modified p-median model* incorporates estimated response time to optimally assign each subdivision to a fire station given a fixed configuration of stations. An optimal assignment minimizes *total estimated response time*, which sums estimated response times over the historical set of FP&EMR calls. The p-median model is "modified" because it can constrain the *maximum station workload*, which is the busiest fire station's assigned number of FP&EMR calls over the time horizon of the data. Optimal, total estimated response time is computed by the modified p-median model for different configurations of the three current Monterey fire stations and the NPS fire station to evaluate these options: (1) The city acquires and operates the NPS fire station while closing one of its current stations, (2) the city closes the NPS station and serves

current NPS customers from city stations, (3) the city acquires and operates the NPS Station and continues to operate the current city stations, or (4) the status quo is maintained.

Overall results indicate that city fire stations can, on average, satisfy federal response-time standards to the subdivisions currently served by the NPS station. However, average (estimated) response time is an incomplete measure of actual response time, so prediction intervals for estimated response times are calculated. One interval indicates that the best city station would satisfy the federal standards for one NPS subdivision only 53% of the time; the existing NPS station satisfies those standards 96% of the time. Thus, the city and NPS are ill-advised to choose option (2).

Monterey and NPS fire stations provide FP&EMR services to their respective areas adequately, but they do not do so as effectively as possible. (NPS has federal standards to meet, which it does, on average.) The All-Four station configuration, which allows any of the four currently operating fire stations to respond to any emergency in the city and to subdivisions currently served by the NPS Station, provides a decrease in total estimated response time of over 7.5% compared to the status quo. This configuration also has a 14.0% lower maximum station workload compared to the status quo. (Maximum station workload is unconstrained in all results discussed here.)

If the All-Four configuration, option (3), is not a viable option, this thesis recommends using the Best-Three configuration, which uses city Stations 1 and 2, and the NPS Station, but closes city Station 3. This configuration, which falls under option (1), results in a 4.9% reduction in total estimated response time compared to the status quo—and uses one less fire station. Compared to the three current city stations alone, designated the Three-w/o-NPS configuration, the Best-Three configuration yields a reduction in total estimated response time of 9.4%. The Best-Three configuration also has a 7.0% lower maximum station workload compared to the status quo, and a 4.5% lower value than the Three-w/o-NPS configuration.

If the city of Monterey does not use the NPS Station, we recommend that the city examine alternate locations for Station 3 (located at 401 Dela Vina Ave near the northeast boundary of the city). Results clearly show an overall improvement in total estimated

response time when using the NPS Station instead of Station 3 to respond to emergencies in the city of Monterey. It is reasonable to assume that other potential locations for Station 3 would also provide better response times. The models in this thesis allow the city to evaluate total estimated response times and maximum station workload for alternate station locations.

Efficient, effective location and management of fire protection resources is a transcendent problem. In the US, there are more than a million professional and volunteer firefighters and more than 31 thousand fire departments. The 1998 cost of fire protection was over $18 billion, and direct property loss to fire was still almost $9 billion. Clearly, any contribution that offers improvement may have dramatic impact.

I. INTRODUCTION

The Fire Protection Handbook [National Fire Protection Association 1981] states that fire departments of all sizes face two fundamental problems, specifically, competition with other agencies for scarce tax dollars, and efficient and effective use of existing resources. The Handbook goes on to recommend that officials collect, organize and interpret data, and use mathematical models to understand and evaluate present doctrine and policies. This thesis, requested by the city of Monterey, California and the US Naval Postgraduate School (NPS), heeds the Handbook's advice by evaluating an opportunity created under Public Law 103-337, Section 816 (US Code 1994) authorizing Department of Defense (DoD) assets in Monterey County to contract municipal services. Currently, the city of Monterey supplies fire protection and emergency medical response (FP&EMR) to the Presidio of Monterey (POM), a 1.3 square mile US Army facility, located within Monterey. This thesis helps the city evaluate its ability to undertake a similar arrangement with the NPS, a 0.9 square mile US Navy facility also located within Monterey.

Response time is the time between a telephone call that leads to the dispatch of an emergency vehicle and that vehicle's arrival at the scene of the emergency. This thesis uses historical response times from each fire station to each city *subdivision*, a small, homogeneous section of the city (including NPS and POM), to develop time-distance models based on linear regression. For a given configuration of fire stations, these models enable evaluation of (1) *estimated response time* which is the predicted average time for a given fire station to respond to an emergency in a specific subdivision, (2) *total estimated response time* which sums estimated response times over all "potential emergencies," and (3) *maximum station workload*, the busiest fire station's total number of potential emergency responses. (A representative set of potential emergencies is derived from historical data.) A *modified p-median model* assigns fire stations to subdivisions in order to minimize total estimated response time and can limit maximum station workload. The purpose of all this modeling is to evaluate different configurations of fire stations for effectiveness: (1) The city may acquire and operate the NPS fire station while closing one of its current stations, or (2) it may serve current NPS customers

from city stations, or (3) it may acquire and operate the NPS Station and continue to operate the current city stations, or (4) it may maintain the status quo.

A fire station provides primary FP&EMR for any call within its assigned subdivisions. This thesis assumes all emergency responses are from the fire station with primary responsibility and bases all analyses on one year's call data consisting of each call's location, responding fire station, response time, date and time. No distinction is made between fire calls, medical calls, or false alarms.

Assuming an empirical (historical) distribution of FP&EMR calls in each subdivision, the modified p-median model assigns each subdivision to one station in a fixed configuration of stations to minimize the total estimated response time, subject to constraints. Without workload constraints, the assignment is always to the available station having the shortest estimated response time. Workload constraints modify the standard p-median model to help evaluate how total estimated response time increases when workload is more equitably distributed among stations. By varying potential fire station configurations, the models allow objective comparisons of total estimated response time and workload. These comparisons will facilitate the selection of the best station configuration if the city takes over the NPS subdivisions, and facilitate analysis of potential future subdivision assignments, regardless of the decision regarding NPS.

A. AREAS OF RESPONSIBILITY

The Monterey City Manager and Fire Chief manage FP&EMR for the 8.8 square mile area comprising the city of Monterey, POM, and the adjoining communities of Del Rey Oaks, and Sand City. The city of Monterey currently maintains three fire stations, staffed at all times. Figure 1 depicts all fire station locations, along with their current *areas of responsibility*. These areas are city divisions where a given station provides primary FP&EMR. Fire Station 1 is at the intersection of Pacific and Madison Streets, Fire Station 2 is at 582 Hawthorne Street and Fire Station 3 is at 401 Dela Vina Avenue.

All military facilities in the Monterey Bay area, except POM, receive FP&EMR from two fire stations, one at NPS, and one at the former Fort Ord. The Navy Shore Establishment Fire Protection/ Prevention Program [Naval Facilities Engineering

Command 1989] classifies NPS as a Class A-1 facility, a designation that requires a full-time, on-site, fire-fighting force. The current fire station located at NPS handles FP&EMR calls at NPS, La Mesa government housing, the Navy Golf course, and the Fleet Numerical Meteorology and Oceanography Center (FNMOC) (Figure 2). The city is considering the provision of FP&EMR only for areas currently served by the NPS fire station. (Montenero [1999] considers the fire station on the former Fort Ord too far northeast of Monterey to be of value to Monterey.) City use of the NPS fire station would comply with the portion of the Naval Facilities Engineering Command Program requiring a full-time, on-site fire-fighting force, but closing the NPS station may also be possible and is considered in this thesis.

The p-median approach, which involves solving an integer-linear program, divides an area of responsibility into smaller subdivisions and assumes all demand in each subdivision occurs at a single representative point [Pollock et al. 1994]. Performed with advice from the Monterey city fire department, subdividing the city based on "access" and size yields 25 subdivisions. All locations within a subdivision have the same primary route, or access, from a given fire station, and each point in a subdivision is estimated to be, on average, within one minute of the center of that subdivision. The NPS fire station area of responsibility has four natural subdivisions: La Mesa housing, the NPS campus, the Navy golf course and FNMOC. Figure 2 depicts all 29 subdivisions.

B. MEASURE OF EFFECTIVENESS

To evaluate the relative desirability of assigning a subdivision to a fire station, appropriate measures of effectiveness (MOEs) must be defined. The best MOEs of any time-critical service are the value of property damage prevented, the number of lives saved, and the quality of life improved [Kolesar and Blum 1973]. The time between a call dispatching an emergency vehicle and its arrival at the scene, the response time, provides an indication of how well the time-critical service is delivered. Response time is an important measure, and often the only measure, of the effectiveness of FP&EMR services [Kolesar and Blum 1973]: response time is the primary MOE for this thesis.

This thesis assumes all emergency responses are from the fire station with

Figure 1. A map of the city of Monterey showing the location of the Monterey and Naval Postgraduate School (NPS) fire stations and their current *areas of responsibility*, divisions where a station provides primary fire protection and emergency medical services. The NPS fire station provides these services only to federal property outlined in green. The city is considering the provision of contract fire protection and emergency medical services to the areas currently served by the NPS Station. [Map adapted from Defense Mapping Agency 1993]

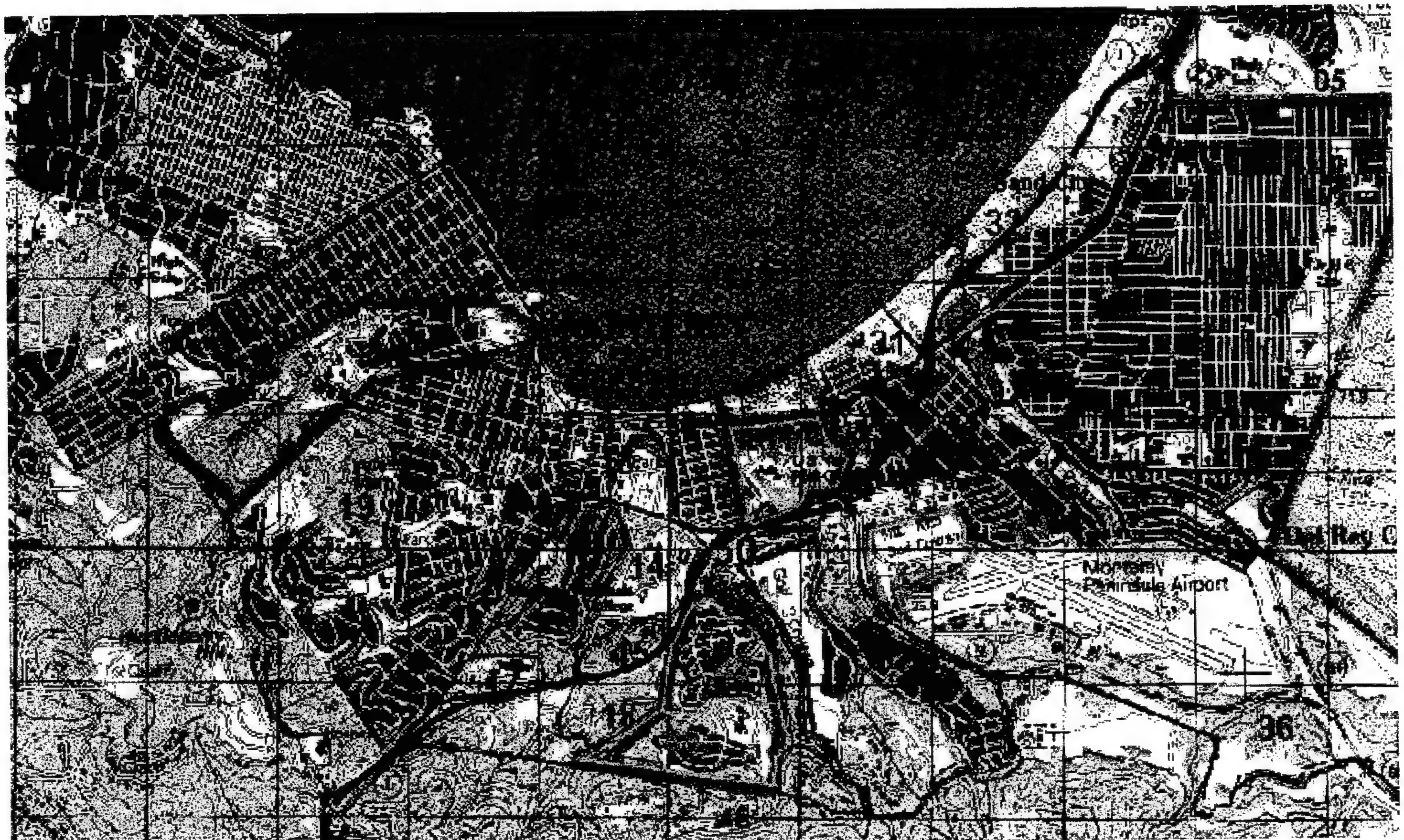

Figure 2. A map of the Monterey area depicting the *subdivisions*, which are small homogeneous sections of the city in which all emergencies are assumed to occur at a single representative point. Fire stations 1, 2, 3, and NPS (currently) respond primarily to fires in subdivisions 11-19, subdivisions 21-25, subdivisions 31-36, and subdivisions 41-45, respectively. Performed with advice from the Monterey city fire department, the city is subdivided based on access and size to yield 25 subdivisions, all having the same primary route, or access, from a given fire station. This thesis estimates response times from fire stations to subdivisions where no historical data exists, and solves a modified p-median integer-linear program, to assign subdivisions to fire stations. [Map adapted from Defense Mapping Agency 1993]

primary responsibility for that area. The data provided by the city of Monterey (Chapter 3) show that the first responding vehicles (similar to the vehicle in Figure 3) are from the fire station responsible for servicing the area containing the emergency over 96% of the time. Thus, an incoming call for FP&EMR service finds the fire station with primary responsibility for that area free at least 96% of the time. (See Rider [1976] for a similar discussion and conclusion about emergency response in New York City.) Additionally, this thesis examines the response times of vehicles dispatched from the next-closest fire station in the event of the primary fire station is not available, or is on scene and requires additional fire-fighting assets.

In a pioneering study of New York City fire service operations, Kolesar, Walker and Hausner [1975] show that time of day has little effect on response time, and for most purposes, can be ignored. This thesis also assumes the time of day does not alter response time. However, it does investigate a potential time-of-year effect because Monterey officials speculate that the Monterey tourist season traffic can influence response time.

Estimated response time is not a completely satisfactory MOE because DoD establishes and publishes acceptable limits on response times at its installations: DoD Instruction 6055.6 mandates maximum response times for fire engines when responding to fires of different types. The maximum time for a machine shop, laboratory, or warehouse fire is five minutes. Administrative offices and Bachelor Officer Quarters have a seven-minute maximum response time. Fires in single- and multiple-family dwellings have a maximum response time of nine minutes [DoD Instruction 6055.6]. These categories cover all buildings at NPS, FNMOC, the Navy Golf course, and La Mesa housing. The Monterey fire department considers a response time of five to six minutes to be desirable [Cooley 1999]. Standards from DoD Instruction 6055.6 must be adhered to whether the responding fire station is from the city of Monterey or a federal fire station.

Data from NPS show that the maximum response time is sometimes exceeded, so in addition to estimated response time we also capture variability using prediction

intervals. For the purposes of this thesis, a *prediction interval* is a span of time in which future values of response times will fall at a computed rate [Devore 1995].

Monterey's Fire Station 1 responds to more FP&EMR calls than Stations 2 and 3 combined. As a secondary MOE, the city would like to examine the effect of a more equitable distribution of workload. The modified p-median model contains constraints to limit the maximum station workload, defined as the yearly number of assigned emergency responses, for the busiest fire station. Redistribution of workload can be accomplished by reassignment of subdivisions to fire stations, or through new fire station locations.

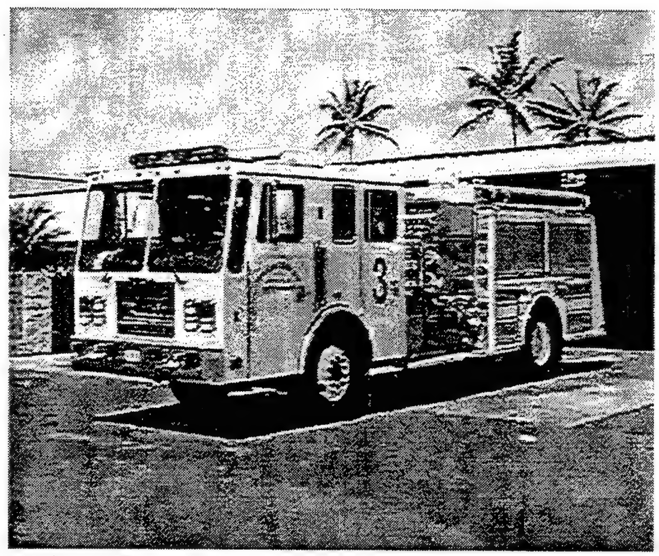

Figure 3. A fire truck similar to those used by the Monterey and NPS fire departments to respond to emergencies. Response time is often the only measure of the effectiveness of emergency services and is the primary measure of effectiveness (MOE) for the thesis. A secondary MOE is the maximum station workload, the yearly number of FP&EMR calls, for the busiest fire station. This secondary MOE is related to how evenly workload divides among stations.

C. DATA COLLECTION

In developing time-distance models and a modified p-median model, this thesis uses data from the Monterey fire department, and the NPS fire station covering 12 months. The two data sets share a nine-month interval and both appear to be representative of a typical year.

DoD Instruction 6055.6 requires the Navy maintain the DoD Fire Incidence Reporting System in an automated management information system format [DoD 1988]. The NPS fire department data include date, time, location of emergency, type of emergency, and response time for emergency calls assigned to the NPS fire station for the period 1 January 1999 to 30 September 1999, but only the numbers and locations of emergencies for 1 October 1999 to 31 December 1999. (Response times for the October through December data become part of the response-time estimation problem discussed later.) The data was printed on paper and the author manually entered the data into an EXCEL spreadsheet [Microsoft Corp 1993] for this analysis.

The Monterey Fire Department provided a printed output of emergency responses, obtained from their database, for the period 3 October 1998 to 3 October 1999 for each of their fire stations. The data include date, time, location of emergency, type of emergency and response time and were all manually entered into an EXCEL spreadsheet by the author. A brief narrative is available for each response, but these narratives are only (easily) accessible from the fire stations' data-entry terminals.

This data provides the input to a linear regression that creates the time-distance models, and also provides data for the modified p-median model.

D. THE THESIS

In the US, there are more than a million professional and volunteer firefighters and more than 31 thousand fire departments [Federal Emergency Management Agency 2000]. The 1998 cost of fire protection was over $18 billion [United States Census Bureau 2000], and direct property loss to fire was still almost $9 billion [Federal Emergency Management Agency 2000]. Clearly, any contribution that offers improvement may have dramatic impact. It is hoped that this thesis contributes to the reduction of both the cost of fire protection and the loss of property.

The remainder of this thesis is organized as follows. Chapter II describes some related operations research studies in time-critical FP&EMR services. Chapter III examines the modified p-median model that is key to subdivision assignment. Chapter IV reviews the process that produces the time-distance models, and explains in detail the

reason for rejection of certain potential predictors of response time. Chapter V describes the results for the time-distance models. Chapter VI reports overall results and Chapter VII provides conclusions and recommendations.

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II. STUDIES ON EMERGENCY SERVICES

In the 1960s, the application of operations research in emergency services began in earnest, and produced a diverse body of published research [Pollock et al. 1994]. Some of this research has application to the examination of emergency services in Monterey.

A. THE RAND STUDY IN NEW YORK CITY

The Rand Fire Project, conducted in New York City at the behest of Mayor John Lindsay, is a groundbreaking study that examines fire-protection services using methods of operations research. The Rand Fire Project, which took place from 1968 to 1976, cost the city $700,000 each year, but saved the city $6 million annually. These savings were due to organizational and cultural changes. The Project was a joint effort using the mathematical expertise of RAND researchers and the knowledge of fire department personnel about day-to-day operations. The Project examined everything from repositioning fire trucks from one station to another during a large fire, to the number of fire stations allocated to a region, to the number of fire companies sent to handle an incoming alarm. This ambitious project involved operations analysts who continued, and in some cases, continue, to work in the field of operations analysis of emergency services. The list includes Peter Kolesar, Edward J. Ignall, Warren Walker, and Kenneth Lloyd Rider [Pollock et al. 1994].

B. OPERATIONS RESEARCH AND THE PUBLIC SECTOR

The text, Operations Research and the Public Sector, provides the urban analyst with a valuable source of information for conducting research. The text states that "In most fire departments…the average availability of units is 95% or more. Consequently, deterministic models have been applied mainly in the fire area" [Pollock et al. 1994]. One of the most useful deterministic models found in this text is the model developed by the English analyst, J.M. Hogg. Hogg first implemented, in the late 1960s, a version of the approach taken by this thesis. In order to determine the optimal location(s) for one or

more fire stations in a city, he divided that city into small subdivisions of similar types of buildings, and assumed all fires in the subdivision occurred at a single representative point in that subdivision. He then determined the travel times from potential fire station locations to every subdivision. This allowed him to minimize the total travel time, given historical or predictive data, for the number of fires in each subdivision for a given period of time [Pollock et al. 1994].

Other important topics explored by Pollock include the merger of services, the number and types of fire equipment to dispatch, and the optimal number of stations and their optimal placement for various objectives.

Another valuable insight Pollock provides is that decisions to close, or relocate fire stations are highly political in nature, and often elicit emotional responses. For example, a study conducted in Trenton, New Jersey showed, definitively, the opportunity to both reduce the number of fire stations and increase the effectiveness of fire response. But, the mayor yielded to political pressure and did not implement the plan.

C. DEVELOPMENT OF URBAN RESEARCH

Rider [1976] examines the availability of a given fire company to respond to fires in its area of responsibility. Rider found that New York City fire-fighting assets were idle 90% of the time, which makes Monterey's 96% "rate of primary station as first respondent" quite believable. Rider's parametric model provides a tool for planners faced with a large city having clusters of FP&EMR calls, and infrequent calls at locations some distance from the majority of calls. The model allows decision-makers to create a balance between minimizing total estimated response time and constructing a plan to approximately equalize the mean travel times to all city locations. This trade-off could be critical if the distant location is a hospital, a high-rise building, or other place with the potential for large loss of life.

Kolesar [1975] examines time-of-day effects on response time with a statistical analysis of over 2,000 observations. He finds that even rush hour has little effect on response time. Kolesar advocates ignoring time-of day-effects on response time for "most planning purposes." Again, it is reasonable to assume that since rush hour in New

York City has little effect on response time, time-of-day has little or no effect on response time in the decidedly less manic Monterey. Kolesar also created a model to predict travel times, given a distance, in New York City. This model combines a square-root submodel for short distances and a purely linear submodel for longer distances. The distance, which determines the submodel to use, is twice the distance required to achieve cruising velocity, which is slightly more than 30 miles per hour. In New York City, this distance is approximately one half mile. In both submodels, the only predictor is distance. Kolesar's logic was that for shorter distances, emergency vehicles never reach their cruising velocity. One minor difference between Kolesar's model and the model used in this thesis is that Kolesar uses travel time and this thesis uses response time. *Travel time* is the time between the start of vehicle movement to the scene of the emergency, and the arrival of that vehicle at the scene; it therefore does not include the additional time from call receipt to the start of vehicle movement. The city of Monterey and NPS record response times only.

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III. A MODIFIED P-MEDIAN MODEL

This chapter presents a modified p-median model to optimally assign each subdivision to a fire station given a fixed configuration or candidate set of stations. An optimal assignment minimizes total estimated response time. The p-median model is "modified" by an additional constraint that limits the maximum station workload. The modified p-median model follows. (An "unmodified p-median model" is defined by simply deleting constraints (4).)

Indices

s	Subdivisions served by the Monterey fire department and the NPS fire station; and
e	Existing fire station locations.

Sets

OPEN	Set of open fire stations;
CLOSE	Set of closed fire stations;
PROHIBIT	Set of (s,e) assignments prohibited by maximum response-time limits or other considerations; and
REQUIRE	Set of (s,e) pairs required by external considerations.

Data

$TIME_{se}$	Estimated time to travel from station e to subdivision s (minute);
$FIRE_s$	Total number of emergencies in subdivision s (event);
STATIONS	Total number of fire stations (station); and
PERCENT	Maximum allowable percent of emergency calls one station may service (event/event).

Binary Variables

$assign_{se}$	1 if a fire station in location e has primary responsibility for all emergency responses in subdivision s; and

$location_e$ 1 if a fire station is located at site e.

Formulation

$$\text{minimize} \sum_s \sum_e FIRE_s TIME_{se} assign_{se}$$

Subject to:

(1) $$\sum_e assign_{se} = 1 \quad \forall s$$

(2) $$assign_{se} \leq location_e \quad \forall s, e$$

(3) $$\sum_e location_e = STATIONS$$

(4) $$\sum_s FIRE_s assign_{se} \leq \frac{PERCENT}{100} \sum_s FIRE_s \quad \forall e$$

(5) $$location_e \in \{0, 1\} \quad \forall \ e$$

(6) $$assign_{se} \in \{0, 1\} \ \forall \ s, e$$

(7) $$location_e \equiv 0 \quad \forall \ e \in CLOSE$$

(8) $$location_e \equiv 1 \quad \forall \ e \in OPEN$$

(9) $$assign_{se} \equiv 0 \quad \forall \ (s, e) \in PROHIBIT$$

(10) $$assign_{s,e} \equiv 1 \quad \forall \ (s, e) \in REQUIRE$$

The objective function minimizes the total estimated response time using estimated response times developed from the historical data. $TIME_{se}$, represents travel time from fire station e to subdivision s. If subdivision s is currently assigned to station e, then $TIME_{se}$ represents the historical response time. If there is no historical data for that pairing, this thesis uses time-distance models to predict the estimated response time. Thus, the objective function combines empirical averages and predicted averages, but may still be viewed as computing an expectation (when normalized) with respect to the empirical distribution of FP&EMR calls. The distance used in the time-distance models is

computed from the estimated center of the subdivision (estimated by "eyeball") to the fire station location, and this is found by either driving the route, or by using a commercial map program [Mapquest.com 2000].

Constraints (1) ensure assignment of each subdivision to exactly one fire station. Constraints (2) allow station-to-subdivision assignment only for a located fire station. Constraints (3) ensure that the number of fire station locations matches the number of operating fire stations, and constraints (4) limit the number of responses from any one fire station to a given percentage of the total number of responses. Constraints (5) and (6) are the binary restrictions on variables and constraints (7)-(10) allow fixing of variables. For example, constraints (8) can prohibit the assignment of a subdivision to station if the estimated response time for that assignment is unreasonably long.

The modified p-median model requires various inputs. A *PERCENT* input of 100 implies that the program will assign each subdivision to the open fire station with the fastest estimated response time. A *PERCENT* input of less than 100 limits the percentage of calls serviced by any one fire station to *PERCENT*. Varying *STATIONS* shows the effect of varying the number of fire stations on total estimated response time and subdivision assignment and allows the model to choose the best configuration of fire stations when *STATIONS* does not equal the total number available. (For the small number of fire stations considered in this study, the model could easily be solved for each reasonable configuration of fire stations. This would obviate the need for *STATIONS* and constraints (3), but these constructs are kept for the sake of completeness.)

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IV. TIME-DISTANCE MODELS

Response times are estimated in this thesis using one or two linear time-distance models for each station's area of responsibility. Before presenting the details of these two models (in Chapter V), this chapter discusses issues of data, an alternative model type and the appropriateness of linear models given the data.

A. CULLING DATA

During the construction of the time-distance models, data entry into EXCEL showed several extreme data points. These data points, while few in number, had a disproportionate effect on the estimated response times. Careful examination of the NPS data show two ten-minute responses to subdivision 45, a government housing area, that are not to a house address, but to a fire road behind the housing area. Since there is no government standard for response time to an access road, these two events are not included in the analysis.

The city of Monterey also has some response times that are much longer than the mean to that subdivision. The data-entry specialist for Monterey's emergency response database determined that some of the calls were false alarms and the responding units, informed of that en route, proceeded to the scene with no sirens or lights and no sense of urgency. A few of the extreme data points have no obvious reason for their relatively long response times and are included. A small portion of the data, less than 0.5%, had incomplete addresses and could not be assigned to any subdivisions. These data points, none of which have long response times, are useless and are discarded.

B. TIME OF YEAR AS A PREDICTOR

Using ARC statistical software [Cook and Weisberg 1999], an F-test checks the hypothesis that response time varies with time of year. The F-test shows insufficient evidence to reject the hypothesis that time of year does not affect response time. Thus, there is still a chance that time of year has some effect, but the effect is probably so small that it can be disregarded in the remainder of this thesis; it is.

In addition to time of year, this thesis examines the indicator variable "August" as a potential predictor because Division Chief Cooley [1999] believes August is the worst month of the year for traffic congestion in Monterey. Linear regressions with and without an August indicator variable show that an August indicator increases the R-Squared value by less than 0.009, and in some cases, much less; and the t-values are very low. A low t-value indicates a relatively large standard error and shows the value of August as a predictor for response time is poor [Williams 1992].

C. THE NEW YORK CITY TIME-DISTANCE MODEL

Kolesar [1975] provides a model for predicting travel time, *T(D)*, given distance, *D*, based on his seminal New York City fire protection project. His model, which might be appropriate for the current study, is:

$$T(D) = \begin{cases} 2(D/a)^{1/2}, \text{ if } D \leq 2d_c \\ (v_c/a) + D/v_c, \text{ if } D > 2d_c \end{cases}$$

where $a \equiv$ acceleration of the emergency vehicle;

$D \equiv$ distance from fire station to location of emergency;

$d_c \equiv$ distance required to achieve cruising velocity;

$v_c \equiv$ cruising velocity; and

$T(D) \equiv$ travel time.

Kolesar's research shows d_c is approximately one half mile, or less. When D is greater than $2d_c$, Kolesar's model is linear.

Table 1 shows historical data for time-distance pairs in Monterey that Kolesar's model cannot accurately predict when applied universally to all areas of responsibility. For example, the response time to travel 0.6 miles in Station 2's area of responsibility is 4.15 minutes, but it takes 3.76 minutes, on average, to travel 0.9 miles, 50% farther, in Station 1's area of responsibility. Also, the response time to travel 0.3 miles ranges from 2.07 minutes to 4.39 minutes, a huge difference. One reason for this may be the non-homogeneous nature of Monterey. For instance, Station 2's small area of responsibility

contains many buildings in close proximity to each other, whereas Station 3 has a large area of responsibility and buildings further apart.

A better fit to the Monterey data could be obtained by using separate versions of Kolesar's model for each area of responsibility. That is, the parameters d_c and v_c could be estimated separately for each area. (This would be a daunting task in New York City; it is understandable that Kolesar uses a single parameter set.). Regression techniques could be used to estimate those parameters but the non-linear, two-piece nature of Kolesar's model means that the full power of linear regression would not be available. In particular the theory of prediction intervals, which is exploited in Chapter V, would not apply. Consequently, this thesis prefers linear models and investigates their appropriateness next.

D. LINEAR TIME-DISTANCE MODELS: CONSIDERATIONS

Before accepting that a linear time-distance model is appropriate, we should ensure there is no evidence of increasing variance (equivalently, standard deviation) with increasing distance. Looking at Table 2, the standard deviation of all subdivisions with more than 20 observations varies by less than 0.9 minutes, and the largest distance does not have the largest standard deviation. When using variance of subdivisions with more than 40 observations, the entire range of variance is slightly greater than one minute.

There are several cases in which a shorter distance actually has a larger variance. The non-constant variance test in ARC rejects the hypothesis that the variance is non-constant, and thus it is reasonable to assume that the variance is non-increasing with increasing distance. Although it is possible that the variance is non-constant, the change is so slight, and the linear model is so accurate (see Chapter V, section A), that this thesis assumes constant variance.

Another consideration in time-distance modeling is the use of logarithm and power transformations in the regression. Distance may be subjected to both log and power transformations with the power transformations include distance squared and the square root of distance. In all cases, transforming predictors yields virtually the same

value of R-Squared as the model without transformed predictors, so, the time-distance models use untransformed distance as a predictor.

To Subdivision	From Station 1 miles (minutes)	From Station 2 miles (minutes)	From Station 3 miles (minutes)	From NPS Station miles (minutes)
11	1.3 (4.88)			
12	1.6 (5.59)			
13	0.9 (3.76)			
14	1.1 (4.60)			
15	1.5 (5.90)			
16	1.0 (4.23)			
17	1.5 (4.33)			
18	2.1 (5.84)			
19	1.0 (3.93)			
21		0.3 (3.54)		
22		0.6 (4.15)		
23		0.9 (4.96)		
24		1.1 (5.17)		
25		0.7 (4.43)		
31			0.8 (4.71)	
32			1.9 (6.05)	
33			0.3 (4.39)	
34			0.3 (3.77)	
35			2.5 (6.84)	
36			1.8 (5.95)	
41				0.3 (2.07)
42				1.2 (4.00)
43				1.5 (4.63)
44				1.8 (4.67)
45				2.3 (5.30)

Table 1. This table shows distance from a given fire station to a subdivision in miles and within parentheses the estimated response time, in minutes. For instance, Station 2 responds to a call at 0.3 miles distance in 3.54 minutes, on average, while the NPS Station only requires 2.07 minutes to respond to a call at the same distance. This suggests the need for separate time-distance models for each area of responsibility.

Subdivision/ Distance	Number of Observations	Mean of Response Times	Std Dev. of Response Time	Minimum Response Time	Maximum Response Time
11 / 1.3	72	4.875	1.547	2	10
12 / 1.6	22	5.591	1.681	2	8
13 / 0.9	78	3.756	1.452	1	8
14 / 1.1	35	4.600	1.218	2	7
15 / 1.5	112	5.902	1.355	2	10
16 / 1.0	66	4.227	1.476	2	10
17 / 1.5	64	4.328	1.491	1	8
18 / 2.1	19	5.842	1.425	4	10
21 / 0.3	41	3.537	1.306	1	7
22 / 0.6	20	4.150	1.531	1	8
23 / 0.9	26	4.962	1.341	2	8
24 / 1.1	18	5.167	1.201	3	7
31 / 0.8	34	4.706	1.169	3	7
32 / 1.9	79	6.051	2.038	1	12
33 / 0.3	57	4.386	1.521	1	9
34 / 0.3	217	3.767	1.586	1	10
35 / 2.5	49	6.837	1.886	4	12
41 / 0.3	118	2.068	1.425	1	8
42 / 1.2	2	4.000	0.000	4	4
43 / 1.5	16	4.625	1.668	2	8
44 / 1.8	6	4.666	1.363	3	6
45 / 2.3	20	5.300	2.430	2	12

Table 2. A table of subdivisions with the distance from the fire station with primary responsibility for responding to emergencies in that subdivision. The table also depicts the number of observations, the mean and standard deviation of response time, and maximum and minimum response times of all observations in that subdivision For example, subdivision 11 is 1.3 miles from Station 1, there are 72 responses to subdivision 11 with an average response time of 4.875 minutes and a standard deviation of 1.547 minutes. Of all the response times to subdivision 11, the minimum is 2 minutes and the maximum is 10 minutes. Looking at all entries, we see a relatively constant standard deviation.

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V. TIME-DISTANCE MODELS, TABLES, AND PREDICTION INTERVALS

This chapter reports the linear time-distance models that result from linear regressions, and evaluates these models for predictive power. Additionally, prediction intervals are computed for estimated response times to NPS subdivisions from the NPS fire station and from Station 3. The purpose of this is to compare the effect on response time if Station 3 becomes the primary responding fire station for the NPS subdivisions.

A. THE TIME-DISTANCE MODELS

Within each fire station's area of responsibility, there are very consistent response times over similar distances, but response times for similar distances differ dramatically between areas. Because of this characteristic, each fire station requires at least one time-distance model. (The form of the models is the same; the parameters are different.) Each time-distance model is the result of a linear regression computed using ARC [Cook and Weisberg 1999].

Table 3 displays the time-distance models; they are of the form: *Time* = y-intercept + slope×*Distance*.

We develop two separate time-distance models within Station 1's area of responsibility because, historically, subdivisions 17 and 18 have response times significantly shorter than the other subdivisions. Table 1 shows that the response time to travel the 1.5 miles to subdivision 17 is over a minute and a half less than the time required to cover the same distance to subdivision 15. Also, the response time to travel the 2.1 miles to subdivision 18 is a few seconds faster than the response time to subdivision 15. The map of Monterey shows the probable cause for this disparity. Large roads that travel almost directly from Fire Station 1 to subdivisions 17 and 18 allow very rapid access to those subdivisions. The model for these two subdivisions reflects the fact that they are served by relatively direct, large-capacity roads called *high-speed avenues of approach*. The model predictions compared to historical data for these two subdivisions differ by less than one second, powerful evidence that a separate model is appropriate.

Each model has a relatively low value of R-Squared. This result occurs because subdivision response times have a relatively large variance, and the range of times vary around the mean, almost equally, with no evidence of increased variance for increased response time over the distances modeled. The facts that response times vary almost equally about the mean and variance is relatively constant with respect to distance indicate the linear models are appropriate.

There is an intuitive interpretation of the models in Table 3. The constant may be thought of as the time it takes to complete all preparations and achieve a constant velocity (minus a small correction, specifically, the slope times the distance required to achieve constant velocity). The slope may be thought of as the rate at which the emergency vehicle travels to the emergency once achieving a constant velocity.

The differing values of slope may be the result of the different driving conditions encountered in each area. Many of the roads in the area served by Fire Station 3 are large, high-speed thoroughfares, which are conducive to short response times. The NPS station, which is west of Fire Station 3, has slightly longer response times and must contend with streets that tend to be more urban. The subdivisions assigned to Fire Station 1 appear to suffer the effects of urban traffic, except for subdivisions 17 and 18, served by high-speed avenues of approach. Also, as the location of most FP&EMR training, it is reasonable to assume that Station 1 is the quickest to begin travel to the scene of an emergency. The westernmost station, Station 2, operates among mostly residential streets and has shorter response times than Station 1, but not as short as Station 3 or the NPS Station.

Without collecting additional data, the accuracy of the time-distance models can be tested only for station-to-subdivision pairings for which historical data exists. Table 4 shows the pairings along with the difference between the actual time and the predicted time using the models from Table 3. The largest difference is 28.8 seconds (0.48 minutes). There are 15 pairings with differences of less than 10 seconds, and five of those are less than one second. This very accurate prediction is powerful evidence of the accuracy of the models.

Fire Station	Linear Regression Model
1 (No High-Speed Avenue of Approach)	$0.95 + 3.18D = T(D)$
1 (High-Speed Avenue of Approach)	$0.54 + 2.52D = T(D)$
2	$2.89 + 2.17D = T(D)$
3	$3.50 + 1.34D = T(D)$
NPS	$1.58 + 1.72D = T(D)$

Table 3. Time-distance models for each fire station. Given a distance from a fire station, D, the models predict the estimated response time, $T(D)$. Station 1 has two separate time-distance models since subdivisions 17 and 18 have response times significantly faster than the other subdivisions. Intuitively the constant term may be viewed as the time to complete all preparations and achieve a constant velocity (less a small correction), and the slope may be thought of as the rate the emergency vehicle travels to the emergency.

Subdivision	Historical Response Time (min)	Predicted Response Time (min)	Difference Between Predicted and Historical Times (min)
11	4.88	5.08	0.20
12	5.59	6.04	0.45
13	3.76	3.81	0.05
14	4.60	4.45	-0.15
15	5.92	5.72	-0.20
16	4.23	4.13	-0.10
17	4.32	4.32	0.00
18	5.84	5.83	-0.01
21	3.54	3.54	0.00
22	4.15	4.19	0.04
23	4.96	4.84	-0.12
24	5.17	5.28	0.11
31	4.71	4.58	-0.13
32	6.05	6.06	0.01
33	4.39	3.91	-0.48
34	3.77	3.91	0.14
35	6.84	6.86	0.02
41	2.07	2.10	0.03
42	4.00	3.64	-0.36
43	4.63	4.16	-0.47
44	4.67	4.68	0.01
45	5.30	5.53	0.23

Table 4. An examination of historical response-time data and predicted response times using the time-distance models found in Table 3. This table illustrates the accuracy of the models. For example, subdivision 11 has an historical response time of 4.88 minutes and the corresponding time-distance model predicts an estimated response time of 5.08 minutes, which means the difference is only 12 seconds. The worst prediction has less than a 29-second (0.48-minute) difference from the historical data.

B. THE TIME-DISTANCE TABLE

Using the time-distance models and the distance of every fire station-to-subdivision, we obtain the estimated response times shown in Table 5. It is reasonable to assume that the time-distance models are most accurate over the areas for which historic data is available, and for which the driving conditions most closely resemble that area. The accuracy of the prediction will most likely decrease as the model attempts to predict an estimated response time over a distance spanning a significant portion of another fire station's areas of responsibility. Conversely, it is reasonable to assume higher accuracy

To Subdivision	From Station 1 miles (min)	From Station 2 miles (min)	From Station 3 miles (min)	From NPS Station miles (min)
11	**1.3 (4.88)**	2.1 (7.45)	1.7 (5.78)	0.2 (1.92)
12	**1.6 (5.59)**	2.8 (8.97)	2.1 (6.31)	1.2 (3.64)
13	**0.9 (3.76)**	1.6 (6.36)	1.8 (5.91)	0.7 (2.78)
14	**1.1 (4.60)**	2.3 (7.88)	1.8 (5.91)	0.8 (2.96)
15	**1.5 (5.90)**	2.7 (8.75)	2.3 (6.58)	1.4 (3.99)
16	**1.0 (4.23)**	2.2 (7.66)	2.5 (6.85)	1.7 (4.50)
17	**1.5 (4.33)**	2.8 (8.97)	3.2 (7.79)	2.5 (5.88)
18	**2.1 (5.84)**	3.5 (10.49)	4.0 (8.86)	3.4 (7.43)
19	**1.0 (3.93)**	2.4 (8.10)	3.7 (8.46)	2.4 (5.71)
21	1.2 (4.77)	**0.3 (3.54)**	2.8 (7.25)	1.8 (4.68)
22	2.0 (7.31)	**0.6 (4.15)**	3.6 (8.32)	2.6 (6.05)
23	2.2 (7.95)	**0.9 (4.96)**	3.9 (8.73)	2.9 (6.57)
24	2.5 (8.90)	**1.1 (5.17)**	4.1 (9.00)	3.1 (6.91)
25	2.1 (7.63)	**0.7 (4.43)**	3.7 (8.46)	2.7 (6.22)
31	2.3 (8.26)	2.9 (9.18)	**0.8 (4.71)**	1.1 (3.47)
32	3.8 (10.12)	4.0 (11.57)	**1.9 (6.05)**	2.2 (5.36)
33	2.1 (7.63)	2.7 (8.75)	**0.3 (4.39)**	0.9 (3.13)
34	2.6 (9.22)	3.4 (10.27)	**0.3 (3.77)**	1.6 (4.33)
35	3.3 (11.44)	4.5 (12.66)	**2.5 (6.84)**	1.75 (4.59)
36	4.1 (13.99)	4.9 (13.52)	**1.8 (5.95)**	3.1 (6.91)
41	1.6 (6.04)	2.3 (7.88)	1.0 (4.84)	**0.3 (2.07)**
42	2.3 (8.26)	3.2 (9.83)	0.8 (4.57)	**1.2 (4.00)**
43	1.9 (6.99)	3.1 (9.62)	2.4 (6.72)	**1.5 (4.63)**
44	2.8 (9.85)	3.5 (10.49)	0.8 (4.57)	**1.8 (4.67)**
45	2.8 (9.85)	4.0 (11.57)	3.3 (7.92)	**2.3 (5.30)**

Table 5. This table, similar to Table 1, shows distances from fire stations to subdivisions in miles, and the corresponding estimated response times in parentheses. The bold-faced numbers are historical data and the non-bold faced numbers are the distance and estimated response time in parentheses from the time-distance models in Table 3. For example, subdivision 11 is 2.1 miles from Station 2, and the time-distance model for Station 2 predicts that the estimated response time is 7.45 minutes.

for predictions to subdivisions bordering a station's area of responsibility.

C. PREDICTION INTERVALS

The estimated response times for Monterey city fire stations responding to fires at subdivisions currently served by the NPS fire station (Table 5) meet all requirements set forth in DoD Instruction 6055.6. However, estimated response time is an incomplete measure of actual response time. The models predict the estimated response time for a station-to-subdivision combination, but it is also possible to develop prediction intervals. The prediction interval, which is an interval of plausible values for estimated response time, contains the true mean in the interval a given percentage of the time [Devore 1995]. Although a federal standard for maximum response times exists, few processes with variability can meet a standard 100% of the time. Prediction intervals give an idea of the probable frequency of compliance to the federal standard for each station-to-NPS subdivision pairing under consideration.

The standard formula for a prediction interval [Devore 1995], translated into terms of the time-distance models, is:

$$PI = \hat{y} \pm t_{\alpha,n-2}\sqrt{s_e^2 + \text{var}(b_0) + D^2\,\text{var}(b_1) + 2D\,\text{cov}(b_0, b_1)}$$

where $PI \equiv$ prediction interval for estimated response time;

$\hat{y} \equiv$ estimated response time;

$t_{\alpha,\,n-2} \equiv$ t-statistic;

$n \equiv$ the number of observations;

$\alpha \equiv$ significance level of the t-statistic;

$s_e \equiv$ standard error of the estimate;

$D \equiv$ distance from fire station to emergency location;

$b_0 \equiv$ constant term from time-distance models;

$b_1 \equiv$ slope from time-distance models;

$\text{var}(b_n) \equiv$ variance of b_n; and

$cov(b_0, b_1) \equiv$ covariance of b_0 and b_1.

The values for standard error, variance, and covariance are ARC outputs. Prediction intervals are only calculated for estimated response times to subdivisions currently served by the NPS fire station, the only subdivisions where one or more federal standards apply. When several federal standards apply to a subdivision due to the various facilities it contains, we use the most restrictive.

Table 6 depicts 90% one-sided prediction intervals from the NPS Station, and Station 3 to the subdivisions currently served by the NPS fire station. Two-sided intervals are unnecessary because responses that are "too short" (which might lie outside such an interval on the left) are of no concern. Included in Table 6 are the one-sided prediction interval sizes where the federal standard is the upper bound. Although there is no federal standard for a prediction interval, the chosen 90% value is an arbitrarily large one-sided prediction interval that seems a reasonable standard for evaluating estimated response times. Subdivision 43, in the northern portion of the La Mesa family housing area, meets the standard through the entire 90% prediction interval whether served by the NPS Station, Station 1, or Station 3. Every other NPS subdivision may be served by a

Subdivision	Federal Standard (minutes)	90% Prediction Interval (minutes)		Size of Prediction Interval if Upper Bound is the Federal Standard	
		NPS	Station 3	NPS	Station 3
41	5	0 - 4.16	0 - 7.00	96%	53%
42	5	0 - 5.71	0 - 6.73	80%	60%
43	9	0 - 6.22	0 - 8.86	99%	91%
44	5	0 - 6.74	0 - 6.73	58%	60%
45	9	0 - 7.59	0 – 10.1	98%	74%

Table 6. Prediction intervals for estimated response times from Station 3 and the NPS Station to the subdivisions currently served by the NPS Station. Column one identifies the subdivision; column two is the most restrictive federal standard for maximum response time for that subdivision; columns three and four are the 90% one-sided prediction intervals from the NPS Station and Station 3, respectively; columns five and six give the size of the prediction interval if the upper bound is the federal standard. For example, subdivision 41 has a federal response time standard of 5 minutes. When served by the NPS Station it will have response times of 4.16 minutes, or less, 90% of the time, and when served by Station 3 will have a response time of 7 minutes, or less, 90% of the time. The NPS Station will meet the federal standard 96% of the time and Station 3 will meet the federal response time standard 53% of the time.

city fire station, but with some portion of the 90% one-sided prediction interval outside of the federal standard.

It is possible to compare the one-sided prediction interval for the NPS Station with historical data to evaluate the predictive power of the interval. For subdivision 41, the NPS subdivision with the most observations, the one-sided prediction interval indicates that the federal standard will be met 96% of the time. The data shows 114 of 118 responses met the federal standard for a rate of 96.6%. For subdivision 44, the most time-critical subdivision for the NPS Station, the one-sided prediction interval indicates that the federal standard will be met 57% of the time. The data shows 4 of 6 responses met the federal standard for a rate of 67%. The other NPS Station-to-subdivision pairings have similarly accurate one-sided prediction intervals.

The smaller one-sided prediction intervals for Station 3 compared to NPS seem reasonable given the increased distance Station 3 has to travel to the NPS subdivisions. Although it is not possible to directly compare station 3's one-sided prediction interval for NPS subdivisions using historical data, the intervals do coincide with station 3's response time for similar distances within its current area of responsibility.

Additionally, we can examine the impact of adding one, two, and three minutes to the historical response times for subdivision 41. The estimated response time for Station 3 to subdivision 41 is 2.74 minutes longer than currently required from the NPS Station; adding additional time to the historical response times provides another indication of Station 3's ability or inability to satisfy the federal standard. If each response time is one minute longer, 8 responses (of 118 total) fail to meet the federal standard. At two minutes longer, 13 fail to meet the standard and at three additional minutes, 30 fail to meet the standard. The NPS station fails to satisfy the standard only 4 times, so these are significant increases (although not necessarily as large as the prediction interval would indicate).

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VI. RESULTS

The results focus on four fire station configurations: the status quo (the current fire station configuration), three fire stations with the NPS fire station closed, the best three fire stations, and all four fire stations as city assets. The bulk of computations compare the total estimated response time and the optimal subdivision assignment when the value of *PERCENT* is set to 100, i.e., when maximum station workload is unconstrained. This setting results in the assignment of each subdivision to the fire station providing the shortest estimated response time (among the stations that are open in a fixed configuration of stations or among the best set of stations chosen by the p-median model). Additional computations evaluate the effect of each fire station configuration on estimated secondary response times, and the effect of changing values of *PERCENT*.

The modified p-median program generates using the General Algebraic Modeling System (GAMS) and solves using XA [Brooke et al. 1997] within one minute for all scenarios considered. Figures 4 and 5 summarize the results.

A. AN EXAMINATION OF THE STATUS QUO

In the event the city of Monterey does not provide contract FP&EMR services to NPS, it is still important to evaluate the city's current fire station-to-subdivision assignment for optimality and to establish a baseline for comparisons. The total estimated response time for all emergencies served by the city of Monterey is 11,069 minutes and is 651 minutes for all emergencies served by the NPS fire station for an overall total of 11,720 minutes. The p-median model with *PERCENT*= 100 (essentially then, the p-median model is unmodified), establishes that the current assignments, given the Status Quo, are optimal. That is, any change to the current fire station-to-subdivision pairings will result in an increase in estimated response time to the reassigned subdivision.

B. CLOSING THE NPS FIRE STATION

In this configuration, the city of Monterey, with its current set of fire stations, takes over the responsibility of providing FP&EMR services to the subdivisions currently served by the NPS fire station and closes the NPS Station. With *PERCENT* set to 100, the total estimated response time is 12,291 minutes, an increase of 571 minutes, or 4.9%, compared to the Status Quo. Figure 5 shows that closing the NPS Station results in the largest total estimated response time of all fire station configurations examined. An improvement in estimated response time occurs for only one subdivision, subdivision 44, and that improvement is only six seconds on average.

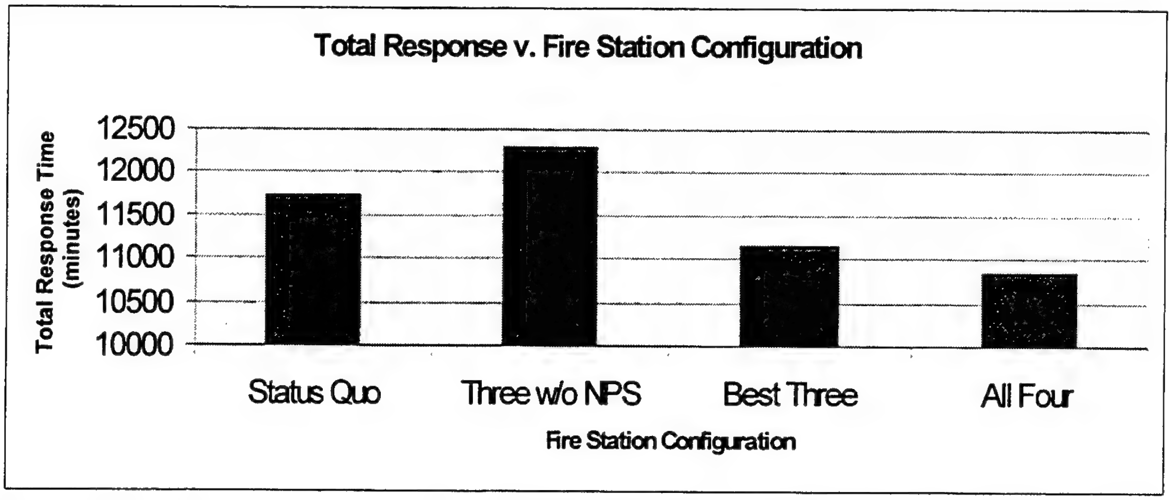

Figure 4. Total estimated response time for various fire station configurations. "Status Quo" is the current fire station configuration without changes to subdivision-to-station assignments. "Three-w/o-NPS" is the three city fire stations without the NPS Station with the city providing FP&EMR services to the subdivisions currently served by the NPS Station. "Best-Three" is the configuration of three fire stations yielding the lowest total estimated response time, with the city providing FP&EMR services to the subdivisions currently served by NPS. The "All-Four" configuration allows any of the four stations to respond to any emergency. This shows, by comparing Status Quo to All-Four, that total estimated response time can be substantially lowered by more effectively using the NPS and city fire stations. Furthermore, the Best-Three station configuration has a total estimated response time only 2.8% slower than the All-Four station configuration while using one less fire station.

C. THE BEST THREE STATIONS

The Best-Three station configuration consists of Fire Stations 1, 2, and the NPS station and has a total estimated response time of 11,143 minutes. This is 1,148 minutes, or 9.4%, faster than using the Three-w/o-NPS configuration, and only 307 minutes, or 2.8%, slower than using All-Four fire stations. The total estimated response time is 577 minutes, or 4.9%, faster than using the Status Quo. Figure 5 helps explain the

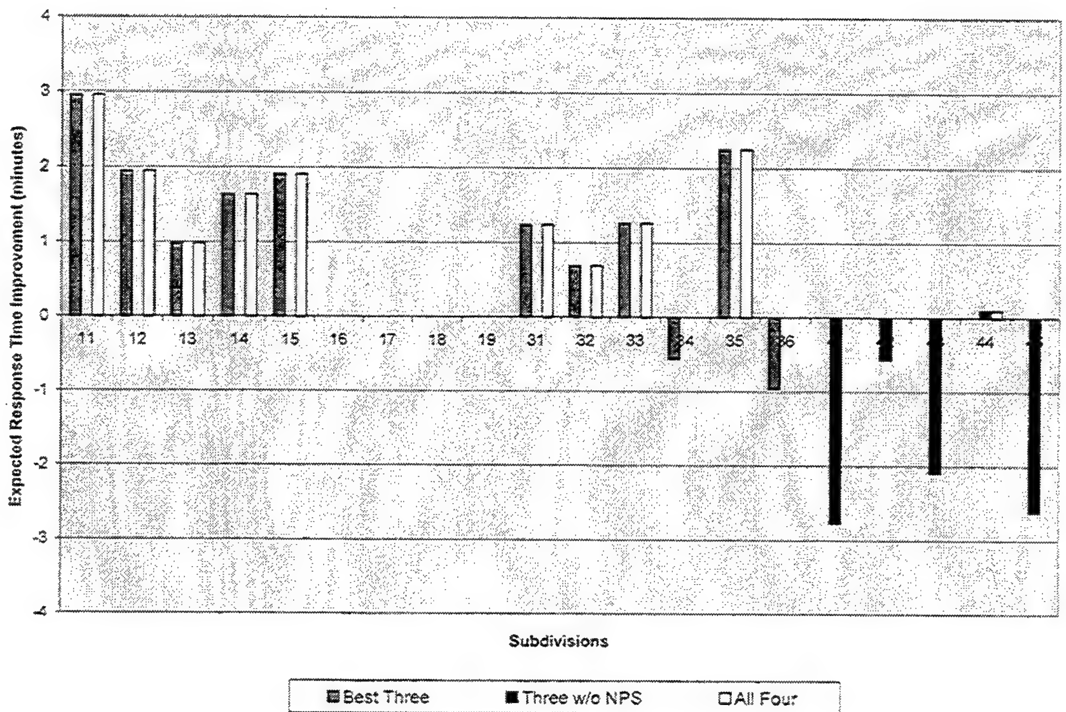

Figure 5. Changes in estimated response time to subdivisions relative to the Status Quo configuration show the effect of subdivision reassignments. Estimated response times improve for all subdivisions in the All-Four configuration. The Best-Three configuration is nearly as good as the All-Four configuration with estimated response times improved for nine subdivisions and worsened for only two. The degradation in estimated response time is, in both cases, less than one minute. The Three-w/o-NPS configuration yields only one improved estimated response time, and that is an improvement of only six seconds. Furthermore, with this configuration, four of the five NPS subdivisions receive longer estimated response times, and the two-family housing areas have estimated response times that increase by over two minutes.

effectiveness of this configuration. From that figure, it is apparent that nine subdivisions, five from Station 1's current area of responsibility, and four from Station 3's current area of responsibility, totaling 538 observations, receive shorter estimated response times. Only two subdivisions, totaling 409 observations, all from Station 3's area of responsibility, receive longer estimated response times. While the number of observations that are shorter is relatively close to the number that are longer, the magnitude of the changes differs greatly. Of the shorter, i.e., improved, estimated response times, 121 would see a reduction in estimated response time of over two minutes, and 260 additional observations would see a reduction of between 74 seconds and two minutes. Of the two subdivisions seeing increases in estimated response times, subdivision 34 with 217 observations has an average increase of 34 seconds, and subdivision 36, with 192 observations has an average increase of 58 seconds. All of the aforementioned changes to estimated response times are relative to the estimated response times in the Status Quo.

A potential concern with closing Station 3 is that response time would likely increase to the southeast corner of Station 3's current area of responsibility, an area known as Ryan's Ranch. Ryan's Ranch is not included as a subdivision in this thesis because only 12 emergencies occurred in that area in the one-year period examined. The subdivision's southeastern edge is 4.3 miles from Station 3 and 6.0 miles from the NPS Station. Using the models found in Table 3, the estimated response times to this southeast corner are 9.3 minutes from Station 3 and 11.9 minutes (2.6 minutes more) from the NPS Station. Thus, estimated response times would increase to this subdivision by about 2.6 minutes if the NPS Station replaces Station 3.

This thesis recommends the use of Stations 1, 2, and the NPS Station if the city is unable to operate the All-Four station configuration. This configuration has 9.4% lower total estimated response time than the Three-w/o-NPS configuration, and performs only 2.8% worse than the All-Four configuration. In the Best-Three configuration, subdivisions 11, 12, 13, 14 and 15 should be assigned to the NPS fire station, and all of the subdivisions currently served by Station 3 should be assigned to the NPS fire station. These would be the only changes to the fire station-to-subdivision pairings.

D. UNRESTRICTED USE OF ALL FOUR FIRE STATIONS

Assigning subdivisions to the fire stations that provide the shortest estimated response time yields a total estimated response time of 10,837 minutes; this is the least total estimated response time of the four configurations examined. Figure 5 shows that every change to a fire station-to-subdivision pairing results in an improved estimated response time when compared to the Status Quo, which is a logical result of removing constraints. In this configuration, subdivisions 11, 12, 13, 14, and 15, which are currently served by Station 1, would be served by the NPS Station. Also, the NPS Station would serve subdivisions 31, 32, 33, and 35, which are currently served by Station 3.

E. RESPONSE TIMES OF SECONDARY FIRE STATIONS

Another potential consideration when evaluating a fire station configuration is the estimated response time of the second-closest fire station to each subdivision. In the event an emergency requires help from an additional fire station, this thesis assumes that the next closest fire station is the one summoned.

Figure 6 shows the estimated response-time changes for the second fire station to respond relative to the Status-Quo configuration. The All-Four configuration shows the greatest reduction in "total estimated secondary response time." Every subdivision currently served by Stations 1 or 3 obtains quicker secondary responses. In each subdivision, the NPS Station becomes the first or second responding station.
Nine subdivisions in the Best-Three configuration would see improved estimated secondary response times.

In the Three-w/o-NPS configuration, the subdivisions served by Station 1 get the same second responding station, Station 3 or Station 2, and hence there is no reduction in estimated secondary response time to any subdivision. The estimated response times for the second responding unit to each NPS subdivision are worse because the primary responding station for the NPS subdivisions is now the station that was the secondary responder, Station 3.

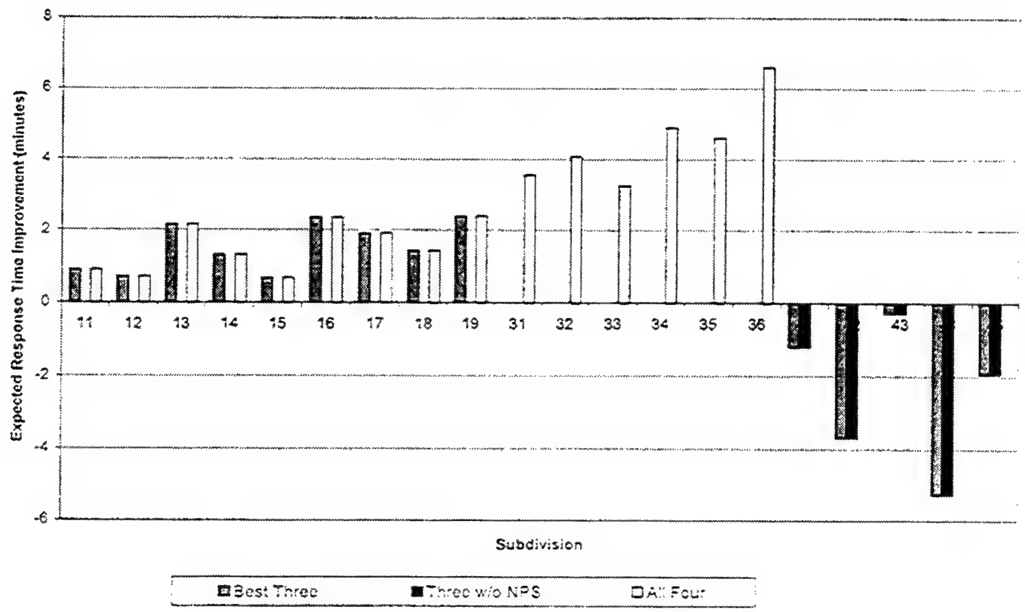

Figure 6. Improvements to estimated response times for the second responding fire station. On occasion, the primary responding fire station may be unavailable and the next closest fire station must respond. The All-Four station configuration results in improved estimated secondary response times for 15 subdivisions. The Best-Three configuration results in improved estimated secondary response times for every subdivision currently served by Station 1 but longer times for every NPS subdivision. The Three-w/o-NPS configuration results in no subdivision receiving improved estimated secondary response times.

F. WORKLOAD DISTRIBUTION

Station 1 responds to more emergencies in the Status Quo than Station 2 and Station 3 combined. Is it possible to redistribute workload with only small changes in total estimated response time? By reducing the busiest station's workload (by reducing *PERCENT* below 100) the total workload must be distributed more evenly. Figure 7 illustrates the effect of limiting the maximum station workload for each configuration.

The maximum station workload varies a great deal among the fire station configurations. As the value of *PERCENT* decreases, total estimated response time begins to increase, but the Status Quo and Three-w/o-NPS configurations allow for adjustment of maximum station workload to approximately 40% without significant

increases in this statistic. Without adjustment, these configurations have a maximum station workload that results in the busiest station responding to 50.5% and 48% of the total number of FP&EMR calls, respectively. Below 45%, total estimated response time

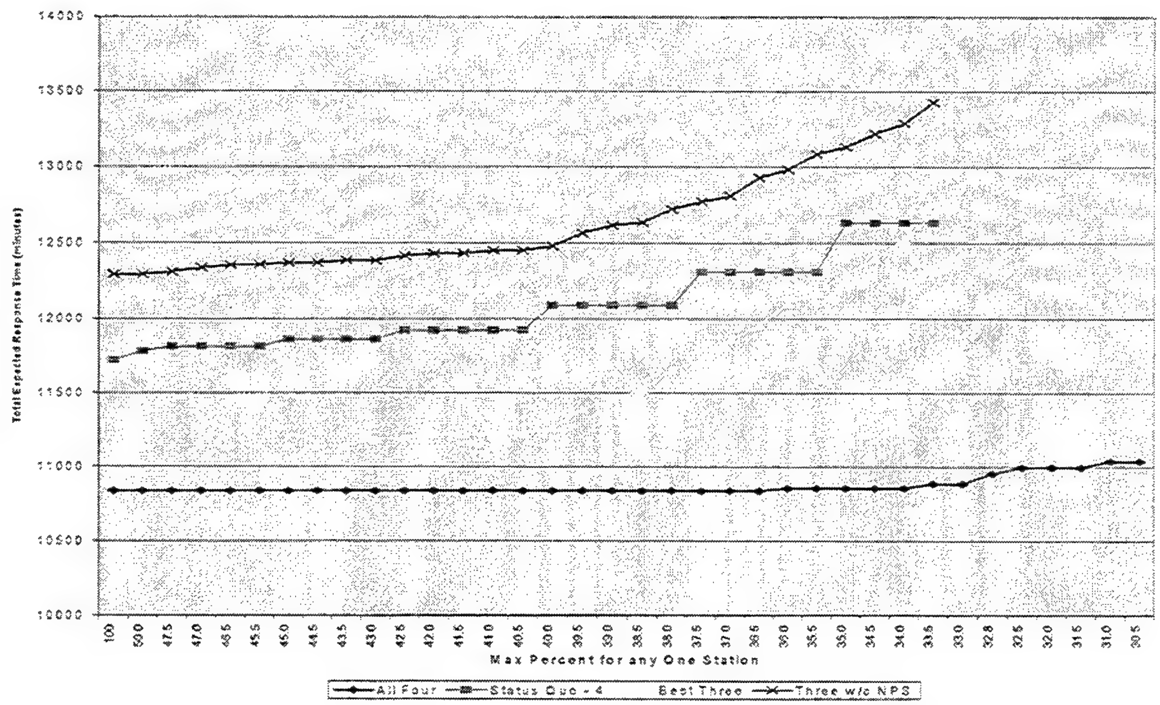

Figure 7. The total estimated response time, in minutes, for various percentages of FP&EMR calls served by any one fire station as the primary responding station. (This percentage is controlled by the parameter *PERCENT*.) As *PERCENT* decreases, and reaches about 50, total estimated response time begins to increase. As *PERCENT* approaches 40 (maximum station workload = 40%), the total estimated response time begins to increase dramatically for all configurations except the All-Four configuration. The Best-Three configuration spreads the workload better than the Status Quo or the Three-w/o-NPS configurations. With *PERCENT* set to 100 there are no constraints on workload, and the maximum station workload, in percent, is 36.5% for the All-Four configuration, 43.5% for the Best-Three configuration, 48% for the Three-w/o-NPS configuration, and 50.5% for the Status Quo configuration. The All-Four configuration gains little from adjusting the workload, and adjusting the workload for the Best-Three configuration results in longer estimated response times for very little reduction in the workload of the busiest station.

increases much faster than the maximum station workload declines. The All-Four and Best-Three configurations reduce the maximum station workload with smaller increases

in total estimated response time compared to the Status Quo or the Three-w/o-NPS configurations. The unadjusted maximum station workload expressed as a percentage of the total number of FP&EMR calls for the All-Four and Best-Three configurations are 36.5%, and 43.5% respectively. Attempts to reduce the maximum station workload in these two configurations result in total estimated response-time increases with little reduction in maximum station workload.

G. ROAD INFRASTRUCTURE DISRUPTIONS

When a disaster disrupts the road infrastructure, the Monterey Fire Department establishes a command post at Station 1. How does a hypothetical road disruption affect estimated response times and the associated subdivision assignments?

For this exercise, the thesis assumes that the Highway 1 bridge at the northwest corner of subdivision 12 has fallen onto Fremont Street (see Figure 2). If any primary station-to-subdivision access routes are cut by this disruption, we recalculate the next shortest path, not using the blocked streets, using a commercial map program [Mapquest.com 2000].

The results of the analysis highlight the robust nature of the general layout of the fire stations in Monterey. In the All-Four stations configuration, or Best-Three, there are no changes to the optimal fire station-to-subdivision pairings. In the Status Quo, or Three-w/o-NPS configuration, reassignment of subdivision 12 to Station 3's area of responsibility minimizes estimated response time. Similar results occur when evaluating other potential disruption points throughout the city. Much of the reason for the optimality of subdivision assignment, even when road infrastructure experiences disruption, may be that most of the bridges in the Monterey area lie near the borders of areas of responsibility. Additionally, the road network typically allows easy rerouting of traffic with respect to single-point failures: There are exceptions, but these occur at the boundaries between areas of responsibility for the fire stations.

VII. CONCLUSIONS AND RECOMMENDATIONS

The Monterey and Naval Postgraduate School (NPS) fire departments provide FP&EMR (fire protection and emergency response) services to their respective areas in a manner that, while acceptable and within federal response-time standards, reduces the effectiveness of both fire departments through handicapping restrictions. In particular, under the "Status Quo configuration," the NPS Station is currently unable to provide FP&EMR services to any city subdivisions, including those literally across the street from the station. This thesis has examined a number of alternative configurations of the current three city stations and the NPS station measured in terms of estimated response times to FP&EMR calls optimally assigned to the configuration.

Ignoring cost implications, this thesis recommends using the "All-Four station configuration," which would allow the quickest responding of the four stations to respond to each emergency in the city and at NPS. This results in a decrease in total estimated response time of over 7.5% compared to the Status Quo. The maximum station workload, the busiest fire station's total number of potential emergency responses, provides another compelling argument for using the All-Four configuration. In particular, this configuration yields 11.5% lower maximum station workload than the "Three-w/o-NPS configuration" (which closes the NPS station and keeps all city stations open), and 14.0% lower maximum station workload compared to the Status Quo. (Maximum station workload is unconstrained in the above comparisons.)

Results indicate that, on average, the optimal assignment of city fire stations can satisfy the federal standards for the subdivisions currently served by the NPS fire station (supposing that the NPS station were closed). However, estimated response time is an incomplete measure of response time. Calculated response-time prediction intervals for one NPS subdivision show that the best city station will only satisfy the federal standard for a particular subdivision 53% of the time, whereas the NPS station satisfies the standard 96% of the time. Closing the NPS station may not be an option that can be implemented immediately.

If the All-Four station configuration is not a viable option for city decision-makers, this thesis recommends using the Best-Three configuration of Station 1, Station 2

and the NPS Station. (Station 3 should be closed.) This configuration results in a reduction in total estimated response time of 4.9% over the Status Quo, while using one less fire station. Compared to the Three-w/o-NPS configuration, the Best-Three configuration results in a reduction in total estimated response time of 9.4% with the same number of fire stations. The Best-Three configuration has 4.5% lower maximum workload than the Three-w/o-NPS configuration, and is 7.0% lower than the Status Quo (when maximum station workload is unconstrained).

If closing the NPS Station is to be considered, this thesis recommends that the city examine alternate locations for Station 3. Results clearly show a reduction in total estimated response time when using the NPS Station instead of Station 3. It is reasonable to assume that other potential locations for Station 3 would also provide better response times. The models in this thesis can be used in the future to evaluate changes in estimated response times and workloads given a relocated station.

This thesis shows that there is no easy way to redistribute the workload without a disproportionate increase in total estimated response time, except through changing the fire station configuration.

The restrictions that prevent the NPS Station from responding to emergencies in the city of Monterey, and prevent the city from responding to emergencies on subdivisions currently served by the NPS Station, hamper the ability to rapidly place an emergency vehicle at the scene of an emergency. Relaxing these restrictions will result in a substantial decrease in total estimated response time, which could result in lives and property saved.

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